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# Carbon dioxide emission scenarios: limitations of the fossil fuel resource

Christopher Vernon[a]*, Erica Thompson[b], Sarah Cornell[a]

[a]University of Bristol, Senate House, Tyndall Avenue, Bristol BS8 1TH
[b]Grantham Institute for Climate Change, Imperial College, South Kensington, SW7 2AZ

**Abstract**

Contemporary increases in atmospheric carbon dioxide concentration are in large part the result of anthropogen carbon dioxide emissions from fossil fuel combustion. Scenario analysis is commonly used to generate projections future carbon dioxide emissions, the resulting atmospheric concentrations and climate impact. In most scenar modelling published to date, carbon dioxide emission scenarios are based on demand-side (socioeconomic ar technology) factors. The fossil fuel resource is assumed ample enough that supply-side factors do not drive futu emission scenarios. This review of the literature on non-renewable resource extraction rate modelling and empiric studies of the global fossil fuel resource base suggests this assumption is unsafe. Supply-side factors can be expecte to drive extraction rates and therefore carbon dioxide emissions as fossil fuel resources become significant depleted. It is likely that the future carbon dioxide emission trajectory will become dominated by supply-side facto during the 21st century. By omitting this possibility, most scenario analysis is too narrow. An implication of suc narrow scenario analysis is that policy driven by the UNFCCC's agreement to "avoid dangerous climate chang targets only demand-side factors to the exclusion of supply-side factors. As supply-side factors come to drive tl carbon dioxide emission trajectory, policy focus should switch from demand-side factors to supply-side factors.


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*Keywords*: emission scenario; SRES; stabilization; Hubbert; fossil fuels; energy policy; supply-side; demand-side; EROI

* Corresponding author. Tel.: +44-(0)117-331-7314; fax: +44-(0)117-928-7878.
*E-mail address*: chris.vernon@bristol.ac.uk.

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## 1. Introduction

The degree of climate change that will be experienced over coming centuries is understood to be strongly influenced by anthropogenic emissions of carbon dioxide [1]. Because the trajectory of future emissions depends on many environmental and socio-economic factors, the Intergovernmental Panel on Climate Change (IPCC) has developed and applied the most widely used family of plausible emission scenarios [2]. The literature includes additional emission scenarios constructed with the aim of stabilising future atmospheric concentrations of carbon dioxide [1], or based on politically acceptable targets of emission reductions, with reference to a baseline year, aiming to limit temperature increase [3-6].

Common to these emission trajectories is their assumed dependence on demand-side factors, that is, population, affluence, global equality and technology choice. These can broadly be termed the anthropogenic driving factors. In contrast, supply-side factors are excluded from the analysis. This paper assesses the lack of supply-side consideration in previous $CO_2$ emission scenario work, and discusses the limitations of the resulting demand-side focus of climate change policy when it is likely that supply-side factors will dominate anthropogenic $CO_2$ emissions within the century.

The terms 'supply-side' and 'demand-side' are used frequently both in relation to factors influencing fossil fuel extraction rates, and to policy initiatives acting towards the goal of the UN Framework Convention on Climate Change (UNFCCC), namely of preventing dangerous climate change [8]. With regard to fossil fuel extraction rates, demand-side factors are socio-economic or technology-related. The embedded assumptions are that the resource can be considered large, with good availability, and the extraction rate is able to meet any demand arising from increasing population, affluence or technology change. When demand-side factors dominate, extraction rates can be determined through socio-economic and technology change modelling. Supply-side factors are primarily related to geology, the magnitude, location and structure of fossil fuel reserves. Once a fossil fuel reserve becomes significantly depleted, previous extraction rates, which had been based on the easily accessible fraction of the reserve, can no longer be maintained and the rate falls. At this point demand and price have little influence and extraction rate is determined by supply-side factors.

With regard to policy, demand-side factors are those that attempt to shape demand for (or consumption of) a resource. These can include taxation and subsidies on the resource itself or on technologies that facilitate its use. The US Car Allowance Rebate System [9] and the UK scrappage scheme [10], both of which subsidise a new efficient car when an old inefficient one is scrapped, are examples of a demand-side factor (even though their primary aim is stimulation of the automotive industry). Supply-side factors are those that attempt to directly manipulate the extraction rate (supply) of fossil fuels. These include the OPEC cartel's quota system and price protection and the Ecuadorian government's proposal to prevent oil extraction and protect the overlying rain forest in exchange for compensation payment [11].

This paper argues that the available fossil fuel resource should be recognised as an ultimately overriding constraint on future emission trajectories, and that supply-side limitations should be considered. Fossil fuel resources constrain both the ultimate contribution of fossil fuel originated anthropogenic $CO_2$ and the future rates of emission. It follows that fossil fuel resources constrain future climate change; at least the major contribution driven directly by fossil fuel originated anthropogenic $CO_2$, rather than other greenhouse gases and land use change (which themselves have indirect relationships to fossil fuel use), the perturbation of natural positive and negative feedbacks in the Earth system, and celestial variations.

Conventional demand-side determined emission scenarios lead to climate change policy which focuses on demand management: carbon markets, taxation, new technology [7]. If the driver of emissions changes from demand-side to supply-side, an alternative set of climate change policies are likely to be more effective, as policy should target a factor with influence over the policy objective. The supply-side influenced emission scenarios outlined here suggest the transition from demand-dominated to supply-constrained emissions will occur this century, an important timescale for contemporary climate and climate policy.

## 2. Many scenario analyses fail to consider the possibility of fossil fuel supply constraints

Scenario analysis has become popular in recent decades as a methodology for exploring the joint impact of various, equally likely, uncertainties. The range of scenarios should be broad enough to cover the range of possibilities, in order to overcome any overconfidence in one's understanding or tunnel vision that may be present [12]. However, supply-side factors are not considered in any of the widely used emission scenarios.

### *2.1. Policy-relevant scenario sets*

The IPCC Special Report on Emissions Scenarios (2000; henceforth SRES) contains a set of 21st century greenhouse gas emissions trajectories, which have been widely used by policymakers and scientists as a representative sample of possible future emissions. These *non-mitigation scenarios* assume no targets, but take into account uncertainty in political and social attitudes as well as technological development and economic growth. However, the extraction of fossil fuels is not explicitly modelled and is assumed always to meet demand.

The IPCC has also used a set of *stabilisation scenarios*, which are not policy-led but describe plausible pathways for stabilisation of atmospheric GHG concentrations at various levels. Uncertainty in the climate system and carbon cycle allows a range of emission scenarios to be associated with a given stabilization scenario. These emission scenarios are not influenced by either demand or supply-side factors.

The final family of emission scenarios in common use are *political targets*. The motivation for developing these is similar to that for the stabilisation targets, driven by the UNFCCC goal to avoid dangerous anthropogenic climate change. The political targets are described as percentage cuts in emissions from an agreed baseline year, typically 1990. They include the G8's 50% reduction in global emissions by 2050 [3], the EU's 20% by 2020 as part of the 20-20-20 plan [4], the UK's own 20% by 2010, replaced in 2008 by the Climate Change Act specifying 80% by 2050 and 26% by 2020 (later amended to 34%) [6] and the Kyoto Protocol's average of 5.2% from 1990 by 2012, with country specific targets [5]. With the exception of the UK's Climate Change Act, interim emission targets are not specified. As with the stabilisation scenarios above, the emission targets are a product of climate system and carbon cycle understanding with further political and economic input. Fossil fuel supply-side factors are omitted from the analysis, and the policy framework discussed for achieving the targets focuses strongly on demand-side factors.

### *2.2. IPCC treatment of fossil fuel constraints*

This paper's criticism of the SRES approach focuses on over-reliance on socio-economic and technology factors to the exclusion of fossil fuel resource and therefore extraction rate constraints. The SRES assumption that there is no supply constraint is justified with reference to the estimates of fossil fuel resource by Rogner [13]. Here, we discuss the limitations of Rogner's study in this context.

An initial shortcoming of Rogner's study is its focus on resource, rather than the future trajectory of extraction rate supported by the resource. Fossil fuel extraction rates start to decline once a significant proportion (typically about half) of the ultimately recoverable resource (URR) has been extracted, and these decreasing rates will have an influence on the emissions trajectories.

A more nuanced shortcoming is the methodology employed by Rogner when compiling fossil fuel resource data. Three classifications of fossil fuels are used: reserves, resources and occurrences. Conventional thinking in the fossil fuel industry does not recognise 'occurrences' as a source of energy, and understands 'resources' will never be fully exploited. The experience of the Forties oil field in the North Sea is typical: the extraction rate rose from nothing in 1975 to 671 thousand barrels per day in 1980, before falling again by almost 99% to just 8.2 thousand barrels per day in 2008. The field is likely to be abandoned within a decade, having achieved a recovery rate of between 62 and 70% of the oil in place [14-15]. Whilst this abandonment could be ascribed to economic factors rather than physical (in an open system it might be cheaper at this point in time to exploit a resource elsewhere), there is a physical constraint limiting the complete extraction of resource in place. If the objective of fossil fuel extraction is to supply energy to society, the resource will only be extracted if it can provide *net* energy after the energy cost of extraction has been subtracted from the total energy extracted. Additionally, the energy cost of infrastructure (cars, roads, etc.) must be 'paid' before oil can be used. Break-even at the well-head is not good enough for extraction to be viable. It is likely that a fraction of the resource will not be able to be extracted in such an energy-positive way and will therefore remain out of reach.

Rogner takes data from a wide range of sources but states: *"The resource base quantities reported ... represent the maximum occurrences of oil, natural gas, and coal derived from the literature. Whenever ranges of estimates were found, the highest plausible value was adopted."* [23]. This has the effect of reclassifying occurrences as resources, and also accumulating high-end estimates that have high associated uncertainty.

Resources, according to the industry categorisation, cannot themselves be extracted: either the technology does not exist or the cost is too high. As technology and knowledge improves resources are reclassified as reserves from which they can be extracted. Rogner notes that in the past, this 'resource-to-reserve mobilisation' has averaged a productivity gain of 1% per year. He extrapolates this rate forward to 2100, dramatically improving available reserves. In our view this is an unjustified extrapolation, assuming a uniformitarian perspective that belies the observed phenomenon of declining energy return on energy invested (EROEI or EROI) [16]. In order to extract fossil fuels (and utilise their embodied chemical energy), energy must be expended. In the early days of a resource's exploitation it is abundant, easily discovered and easily extracted. Naturally the principle of 'best first' is followed: large coal seams near the surface and large oil fields are both the first to be discovered and the easiest to be exploited.

As the resources become depleted, the best, most easily accessed resources are consumed and the task becomes harder. In the case of oil, new extraction is increasingly coming from deep water deposits (such as the recently announced Keathley Canyon discovery in the Gulf of Mexico, which is in 1,259 m of water with a well depth of 10,685 m [17]) or unconventional resources, such as Canada's tar sands, and also shale oil, coal-to-liquids, biofuels and gas-to-liquids which require a great deal of post-extraction processing for use [18]. Critically with all these forms, the EROI decreases.

EROI is a dimensionless ratio. If the energy equivalent of 1 barrel of oil is required to extract 50 barrels of oil, the ratio is 50:1 and 98% of the embodied energy is net energy available to society. This ratio has dramatically declined over time. Hall [16] has calculated that for oil extracted in the US the EROI has declined significantly:

> *"The EROI for oil in the US during the heydays of oil development in Texas, Oklahoma and Louisiana in the 1930s was about 100 returned for one invested. During the 1970s it was about 30:1, and for about 2000 it was from 11 to 18 returned per one invested. For the world the estimate was about 35:1 in the late 1990s declining to about 20:1 in the first half decade of the 2000s."*

This decline has occurred in the background, almost invisibly to Rogner's identified productivity improvements. This has been possible as the decline from 100:1 to 30:1 to ~20:1 only represents a move from 99% energy availability to 97% to 95%, a trivial change in the face of the magnitude of net surplus energy which increased almost four-fold over this time.

Very low EROI sources (Canadian tar sands for example, at <5:1 [19]) are already being turned to, and their exploitation is sustained through energy cross-subsidy from high EROI sources like natural gas. Large volumes of water (2-4.5 barrels of water for every barrel of synthetic crude) are also required in this case, so it is likely that extraction rates in future will not depend on the tar sand resource at all but rather other inputs. This kind of cross-subsidy works in the short term, for a small volume, and while the gas and water are available but does not guarantee the continued exploitation that Rogner – and therefore the SRES – have assumed going forward.

In summary, all 40 SRES scenarios are based on Rogner's fossil fuel assessment, which takes the upper estimates of fossil fuel occurrences in the literature, reclassifies these to resources, and projects an optimistic continuation of historic resource-to-reserve mobilisation. This ignores the principle of 'best first', the increasingly inhomogeneous distribution of remaining resources (limiting access as an increasing proportion of the remaining resources become concentrated in a small number of countries), and the declining EROI. In addition to these criticisms, it ignores the approximately 'bell-shaped' curve widely observed in non-renewable resource exploitation rates, and no assessment is made of the extraction rate trajectory the stated resource can sustain. It is this rate that the scenarios should depend upon, not the magnitude of the reserves.

Whilst Rogner's projection of the future cannot be ruled out, neither should it be counted on. SRES adopts Rogner's conclusion that: *"…neither hydrocarbon resource availability nor costs are likely to become forces that automatically would help wean the global energy system from the use of fossil fuel during the next century." [13]*. Thus supply-side factors are kept outside of the scenario construction process. In our view, this is an over-optimistic conclusion, that has resulted in too narrow a focus of scenarios.

## 3. Fossil fuel extraction modelling

### *3.1. Constraining the extraction trajectories: empirical approaches*

Although the fact that fossil fuel reserves are finite it is not disputed, there is considerable disagreement regarding the effect of this limitation on 21$^{st}$ century fossil fuel extraction, and therefore on carbon emission trajectories.

Several previous studies have modelled resource extraction by curve-fitting to empirical data on past fossil fuel extraction. The most iconic of these studies is the study of M. King Hubbert [20], who proposed that the trajectory for oil production would roughly follow a bell-shaped curve. However, this curve-fitting approach is limited in scope, since it imposes assumptions about the shape of the curve without physical justification. The area under the extraction curve is equal to the total amount extracted, which does have a physical limitation, namely the total geological endowment. Nevertheless, Hubbert's original Gaussian curve and the many variants since on the bell-shaped curve (logistic, exponential, asymmetric) have all demonstrated reasonable agreement with production data, which usually show a characteristic peak and decline modified by local physical, technological and economic parameters.

Three such models of the extraction rate evolution of non-renewable resources, using varying methodologies, have been applied successfully. The first, Hubbert's model, simply fitted a plausible extraction rate profile to an estimated ultimately recoverable resource (URR) [20]. Deffeyes extended this approach by fitting a idealised curve to early extraction rate history, giving a projection of the URR rather than relying on an essentially arbitrary estimation [21]. Bardi and Lavacchi applied the Lotka-Volterra predator-prey model, representing the resource stock as ‘prey’ and the capital employed in its extraction as ‘the predator’ [22]. Just as the predators feed on the prey, the capital stock arises from the profitable extraction of the resource, with the mutual interdependence driving the dynamics of growth and decline. In all these cases, the scenarios’ extraction rate trajectories and the timing and magnitude of the peak extraction rate are not strongly influenced by the magnitude of URR.

Implicit in all these models is the concept of ‘best first’: the easiest resource to exploit (and this may be largely just due to its relative abundance) is extracted first. As these easily extracted resources become depleted, past extraction rates can no longer be maintained and begin to decline. This concept of limited and declining extraction rates, whilst a large amount of resource (typically half) remains, is not represented in any of the $CO_2$ emission scenarios considered above.

### *3.2. Comparison of three different extraction models.*

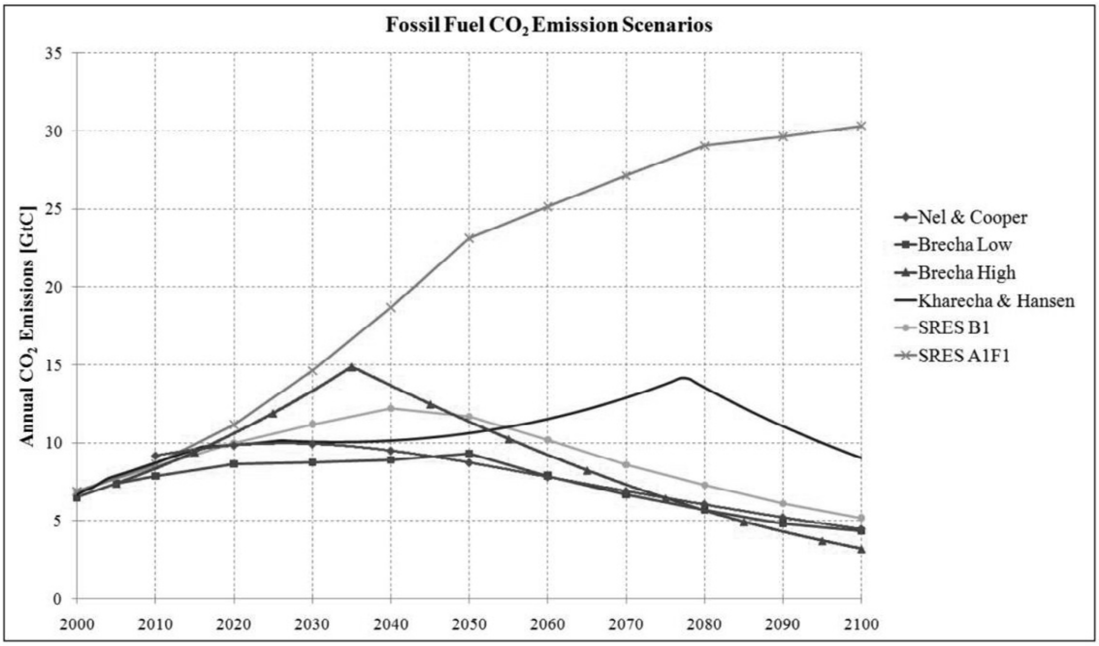
Despite the large volume of scientific literature on climate change, only three peer-reviewed publications have been identified that address the specific question of the impact supply-side constraints have on climate change, and apply declining extraction trajectories to climate projections, and none of these are mentioned in the publications of the IPCC.

The three projections by Kharecha and Hansen [23], Brecha [24] and Nel and Cooper [25] are shown in Figure 1. SRES scenarios A1F1 and B1, taken as representative of the bounds of the SRES family are also shown. Kharecha and Hansen’s methodology is based on an estimation of URR, with data taken from the energy company BP, the US Energy Information Agency, the World Energy Council, and the IPCC. Their non-mitigation scenario (described as Business-As-Usual), assumes that the recent observed 2% per year growth rate in fossil fuel extraction will continue until such time when half of the URR of each stock has been extracted, and thereafter extraction rates decline at 2% per year. The methodology employed in Brecha’s study is qualitatively influenced by Hubbert’s and Deffeyes’ but specific considerations are made for unconventional sources of oil along with conventional oil, coal and gas, and a mathematical extension to the logistic equation is made to include the continual growth of reserves. This continual growth of reserves has parallels to Rogner’s resource-to-reserves mobilisation approach [13], but still produces a clear peak then decline in extraction rates, even from a (mathematically) infinite URR. Finally, Nel and Cooper generate a range of fossil fuel extraction scenarios based on the linearised logistic function described by Deffeyes and coupled economic performance and energy availability (also taking into account nuclear and renewable energy sources).

In all cases, the peak and decline caused by supply-side constraints occurs well within the 21st century, even for high assumptions of URR. The emissions trajectories implicit in the extraction models developed by these three studies are similar in character, although the shape and scale differ. The different models with different assumptions outlined here collectively suggest supply-side factors do provide an important constraint on emissions, assuming that unconventional fossil fuels are not exploited to a significant extent (consistent with the declining EROI described above).

These three studies conclude that atmospheric $CO_2$ concentrations stabilise from approximately 450 to 600 ppm, even without policy intervention, as with the non-mitigation SRES scenarios. Whilst these concentrations are lower than those obtained for many of the demand-side driven scenarios detailed in section 2, there are large uncertainties in both the fossil fuel supply-side factors and also the responses of the coupled climate system and the carbon cycle. The important point is that it is plausible that the current demand-side factors will give way and supply-side factors will dominate in determining future emissions.

**Figure 1.** $CO_2$ emissions scenarios from three modelling approaches [23-25], upper and lower bound scenarios from IPCC SRES.




Given the fundamental significance of anthropogenic $CO_2$ emissions for future climate change, and the plausibility of supply-side constraints impacting $CO_2$ emission trajectories over the comparatively short timescales of decades to a century, we consider that the neglect of this perspective can no longer be justified.

## 4. Transition from demand-side constraint to supply-side constraint

The $CO_2$ emission scenarios routinely used within the scientific climate change and political policy development communities have been dominated by demand-side factors, relying on Rogner's conclusion [13] that *"neither hydrocarbon resource availability nor costs"* would be likely to constrain fossil fuel use this century. If this is indeed the case, then future emissions will be dominated by socioeconomic and technological factors, and policy frameworks aiming to influence future emissions should address these areas.

However, hydrocarbon resources may not be as abundant as Rogner concluded, as the analysis outlined above indicates: their extraction rate trajectories are likely to peak with approximately half the resource remaining, and declining EROI will leave some resource permanently out of reach. In this case, supply-side factors could come to dominate this century.

A common feature in the studies cited above is not only the peaking and transition to supply-side dominance this century, but also the relative order of this transition occurring for each fossil fuel – first oil, then gas and finally coal. The point at which their extraction rate, and the associated emission of $CO_2$, transitions from being a function of demand-side factors to being a function of supply-side factors will differ for the three fuels. The proximity of this transition to the present day defines the degree of freedom or influence that current demand-side policy can have on that resource's associated $CO_2$

emissions. For example, if oil is to become supply-side limited within a decade, as suggested by the three empirical studies in section 3.1, then the current range of demand-side policy initiatives do not have the scope to significantly alter ultimate $CO_2$ emission from oil. (Oil is possibly already experiencing a degree of supply-side limitation, indicated by the high oil prices maintained since 2005 without a significantly increased supply.) In contrast, for coal, the transition from demand-side to supply-side limitation could be several decades away, empowering demand-side policy initiatives.

### *4.1. Policy*

The UNFCCC's stated objective is to avoid dangerous climate change. Given that the magnitude of climate change is strongly associated with atmospheric concentrations of $CO_2$, policy initiatives aiming to deliver that objective need to be targeted where they can most effectively impact atmospheric concentrations. The finite amount of political and economic capital with which to enact change is a further reason for effective targeting.

Coal is the most significant contributor to $CO_2$ emissions this century, and for several decades to come emissions associated with its use are likely to remain determined by demand-side factors. Demand-side policies targeting coal are therefore likely to have the most significant impact on total anthropogenic $CO_2$ emissions in coming decades, a fact that motivated the renowned climate scientist James Hansen to send open letters to British Prime Minister Brown and German Chancellor Merkel [26].

Natural gas is likely to be at least a decade from becoming supply-side limited [27], and will therefore still be responsive to demand-side policy. However, since energy from gas is approximately half as carbon-intensive as coal per unit, heat and electricity generation from combined cycle gas turbines can be >50% efficient compared to ~30% efficient for legacy coal fired power stations [28], so in a situation where $CO_2$ emissions control is the policy goal, the most effective demand-side policy for gas may be to increase its use, as a replacement for coal. Increasing reliance on gas in the short term does carry associated energy security risk, as the gas peak is projected to occur relatively soon.

Oil is likely to become supply-side limited within a decade and as mentioned above, already shows signs of supply-side limitations. For this reason demand-side policy initiatives are likely to be ineffective in regard to the $CO_2$ emission trajectory from oil. Instead supply-side initiatives should be devised and deployed as soon as possible.

### *4.2. Partial Adoption*

From the perspective of the climate system, only global $CO_2$ emissions are of importance, not regional variations. In contrast, policy, whether demand-side or supply-side, cannot be expected to influence the whole world – there can only ever be partial adoption of a policy. Thus, in evaluating policy options one must consider both whether the source of $CO_2$ emissions is in a regime determined by demand-side factors or supply-side factors and also the implication of the inevitable partial adoption of policy.

Up until now, $CO_2$ emissions have been determined by demand-side factors. The global emissions have been the sum of individual regions', countries' and people's demands. In the current world system, supply has been able to meet this demand. Bearing in mind the partial adoption, applying a supply-side policy such as extraction quotas to a particular reserve is unlikely to impact $CO_2$ emissions, as other reserves will be able to increase their extraction rates to compensate. In other words, the system is not supply-side limited, so supply-side policies are not effective. On the other hand, a partially adopted demand-side policy will reduce demand in one region without affecting others. Supply, as the sum of regional demands, will reduce – and with it, global $CO_2$ emissions.

At some point in the future, $CO_2$ emissions will be determined by supply-side factors. The global emissions will be the sum of individual regions', countries' and reserves' supply. Demand will be able to consume all the available supply. Again bearing in mind the partial adoption, applying demand-side policy such as fuel duty is unlikely to impact $CO_2$ emissions as other sources of demand, where the policy is not adopted, will increase to compensate. The system is not demand-side limited. Whereas a partially adopted supply-side policy will reduce supply in one region without other regions being able to compensate, and will result in reduced global $CO_2$ emissions.

## 5. Conclusions

There are four key conclusions:

- Supply-side limits are likely to dominate $CO_2$ emissions during the 21st century.
- Oil, gas and coal become supply-side limited at different times.
- Purely demand-side scenarios are too narrow, diminishing the power of scenario analysis.
- Due to partial adoption, it is important to adopt the relevant policy at the right time.

It is possible that supply-side limits will not prove constraining during the 21st century. For conventional oil and gas however, this is highly unlikely due to the vast reserves required to maintain even a slowly growing rate of extraction. There is greater uncertainty regarding coal and unconventional oil resources, but it is unsafe to assume that not only will these resources not become supply-side limited but their rate of increase of extraction rate will also be able to compensate for the declining conventional oil and gas extraction rates – both implicit assumptions within conventional emissions scenarios.

All the supply-side scenarios reviewed are in agreement that first oil, then gas, and then coal will transition from being demand-side to supply-side constrained. Periods where one resource is limited on the supply-side while others remain demand-side limited require policy to be targeted at each resource for optimal influence.

Scenarios which disregard supply-side limits to fossil fuel extraction rates are too narrow. This paper illustrates plausible scenarios where supply-side factors do dominate $CO_2$ emissions during the societally and climatically relevant time period of the coming century. Such a narrow family of scenarios is at odds with the motivation to carry out scenario analysis, which is to cover the fullest range of possibilities. The SRES family, stabilisation and political target-based scenarios all manifest the same 'tunnel vision' in their construction, disregarding a plausible supply-constrained future, preventing the strength of scenario analysis to be fully utilised.

Any policy will only be adopted partially, and this partial uptake needs to be taken into consideration. If the global system is demand-side determined, as has been the case historically, the inevitable partial adoption of demand-side policy would still have a global impact. Attempting to apply supply-side policy in such a situation is unlikely to have global impact, as regions where it is not adopted will be able to increase their supply to compensate. At some point in the future, when the global system becomes supply-side limited, then the partial adoption of demand-side policies will be ineffective as regions where the policy is not adopted will be able to increase their demand to compensate. However the partially adopted supply-side policy will be effective as no other region will be able to increase their supply to compensate. Closer attention to the issue of 'peak fossil fuel' is needed in order to support the right policy for the context.

Scenario analysis can identify the existence of a transition from demand-side to supply-side limitation for each fossil fuel source. This foreknowledge can be used to prepare policy initiatives ready for their eventual deployment and enable greater influence over the future $CO_2$ emission trajectory. Omitting the possibility of supply-side limitations risks ineffective policy and reduced influence over the future trajectory of $CO_2$ emissions.

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